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Optimizing Satellite Communications Using DoubleTalk[®] Carrier-in-Carrier[®] & CDM-625 Advanced Satellite Modem

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Introduction

Space segment costs are typically the most significant operating expense for any satellite-based service, having a direct impact on the viability and profitability of the service. A satellite transponder having finite resources in terms of bandwidth and power, the transponder leasing costs are determined by bandwidth and power used. For optimal utilization, a satellite circuit should be designed to use similar share of transponder bandwidth and transponder power.

Once the satellite and earth station parameters are fixed, the traditional approach to balancing a satellite circuit involves trade-off between modulation and coding. A lower order modulation requires less transponder power while using more bandwidth. Conversely, higher order modulation reduces required bandwidth, but at a significant increase in power.

Comtech EF Data has added a new dimension to satellite communication optimization – DoubleTalk® Carrier-in-Carrier® (CnC). This innovative technology provides a significant improvement in bandwidth and power utilization, beyond what is possible with forward error correction (FEC) and modulation alone, allowing users to achieve unprecedented savings. When combined with advanced Modulation and FEC, it allows for multi dimensional optimization

- Reducing OPEX
 - Occupied Bandwidth & Transponder Power
- Reducing CAPEX
 - BUC/HPA Size and/or Antenna Size
- Increasing throughput without using additional transponder resources
- Increasing link availability (margin) without using additional transponder resources
- Or, a combination to meet different objectives

DoubleTalk Carrier-in-Carrier

DoubleTalk Carrier-in-Carrier bandwidth compression is based on patented “Adaptive Cancellation” technology that allows the transmit and receive carriers of a duplex link to share the same transponder space. Figure 1 shows the typical full duplex satellite link, where the two carriers are adjacent to each other. Figure 2 shows the DoubleTalk Carrier-in-Carrier operation, where the two carriers are overlapping, thus sharing the same spectrum.

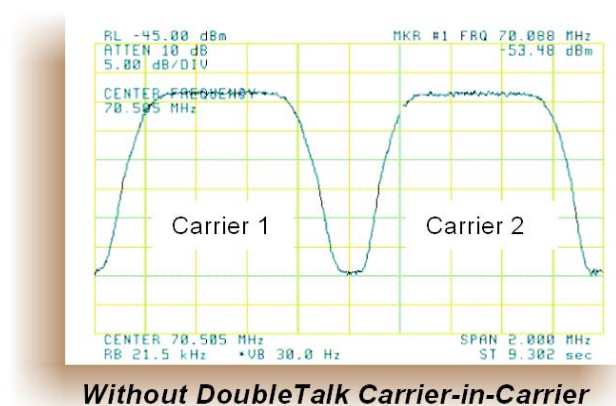


Figure 1 - Traditional Full Duplex Link

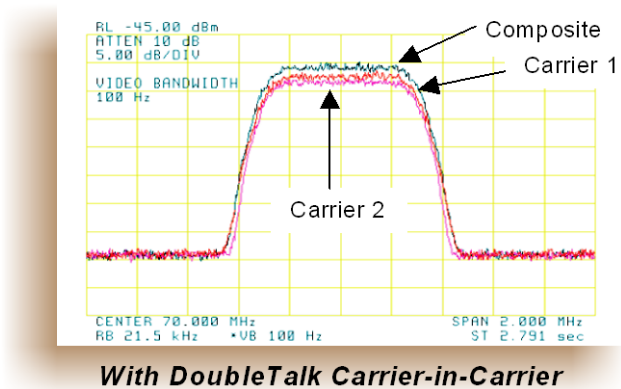


Figure 2 - Duplex Link with DoubleTalk Carrier-in-Carrier

When observed on a spectrum analyzer, only the Composite is visible. Carrier 1 and Carrier 2 are shown in Figure 2 for reference only.

DoubleTalk Carrier-in-Carrier is complementary to all advances in modem technology, including advanced FEC and modulation techniques. As these technologies approach theoretical limits of power and bandwidth efficiencies, DoubleTalk Carrier-in-Carrier utilizing advanced signal processing techniques provides a new dimension in bandwidth and power efficiency.

DoubleTalk Carrier-in-Carrier allows satellite users to achieve spectral efficiencies (bps/Hz) that cannot be achieved with modulation and FEC alone. E.g., DoubleTalk Carrier-in-Carrier when used with 16-QAM approaches the bandwidth efficiency of 256-QAM (8bps/Hz).

Modulation & Code Rate	Spectral Efficiency (bps/Hz)	
	Traditional SCPC	Carrier-in-Carrier
BPSK 1/2	0.50	1.00
QPSK 1/2	1.00	2.00
QPSK 2/3	1.33	2.67
QPSK 3/4	1.50	3.00
QPSK 7/8	1.75	3.50
8-QAM 2/3	2.00	4.00
8-QAM 3/4	2.25	4.50
8-QAM 7/8	2.63	5.25
16-QAM 3/4	3.00	6.00
16-QAM 7/8	3.50	7.00

As DoubleTalk Carrier-in-Carrier allows equivalent spectral efficiency using a lower order Modulation and/or FEC Code, it can simultaneously reduce CAPEX by allowing the use of a smaller BUC/HPA and/or antenna.

As DoubleTalk Carrier-in-Carrier can be used to save transponder bandwidth and/or transponder power it has been successfully deployed in bandwidth-limited as well as power-limited scenarios.

DoubleTalk Carrier-in-Carrier Cancellation Process

In a traditional full duplex satellite connection between two sites, separate satellite channels are allocated for each direction. If both directions transmitted on the same channel, each side would normally find it impossible to extract the desired signal from the aggregate due to interference originating from its local modulator. However, since this interference is produced locally, it is possible to estimate and remove its influence prior to demodulation of the data transmitted from the remote location.

DoubleTalk Carrier-in-Carrier achieves state-of-the-art performance by combining the latest signal processing technology. It continually estimates and tracks all parametric differences between the local uplink signal and its image within the downlink. Through advanced adaptive filtering and phase locked loop implementations, it dynamically compensates for these differences by appropriately adjusting the delay, frequency, phase and amplitude of the sampled uplink signal. The result is excellent cancellation performance.

For the DoubleTalk Carrier-in-Carrier cancellation, it is necessary to provide each demodulator with a copy of its local modulator's output.

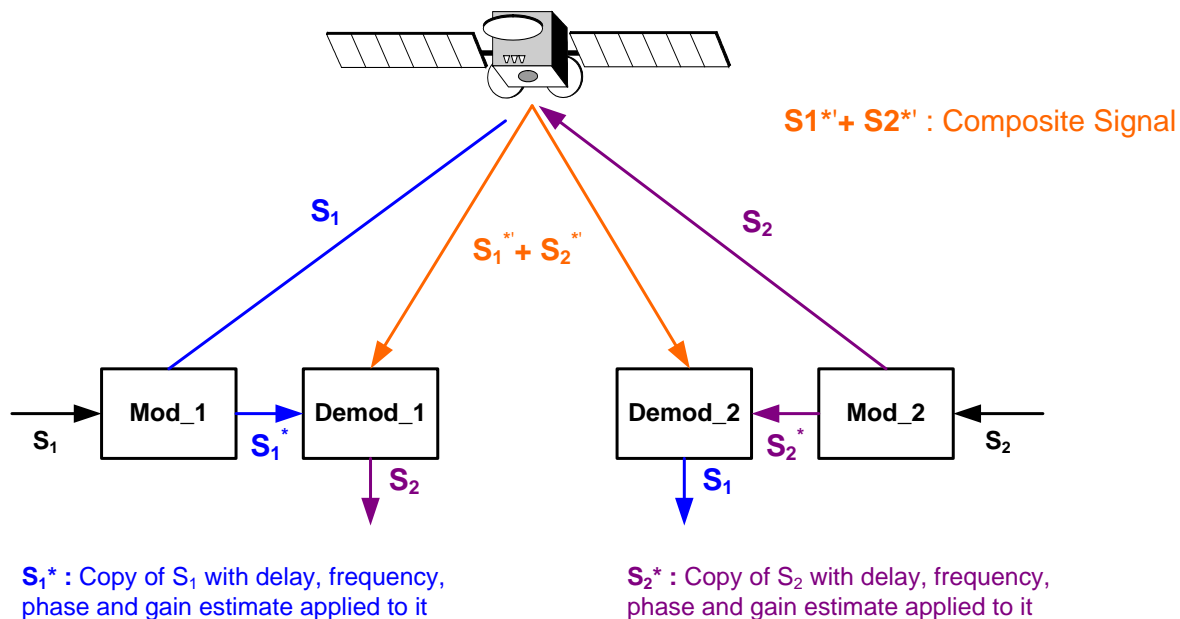


Figure 3 - DoubleTalk Carrier-in-Carrier Signals

For round trip delay estimation, a search algorithm is utilized that correlates the received satellite signal to a stored copy of the local modulator's transmitted signal. The interference cancellation algorithm uses the composite signal and the local copy of S_1 to estimate the necessary parameters of scaling (complex gain/phase), delay offset and frequency offset. The algorithm continuously tracks changes in these parameters as they are generally time-varying in a satellite link.

The resulting estimate of the unwanted interfering signal is then subtracted from the composite signal. In practical applications, the estimate of the unwanted signal can be extremely accurate. Unwanted interfering signal suppression of 30 dB or more has been achieved in commercial products with minimal degradation of the demodulator performance.

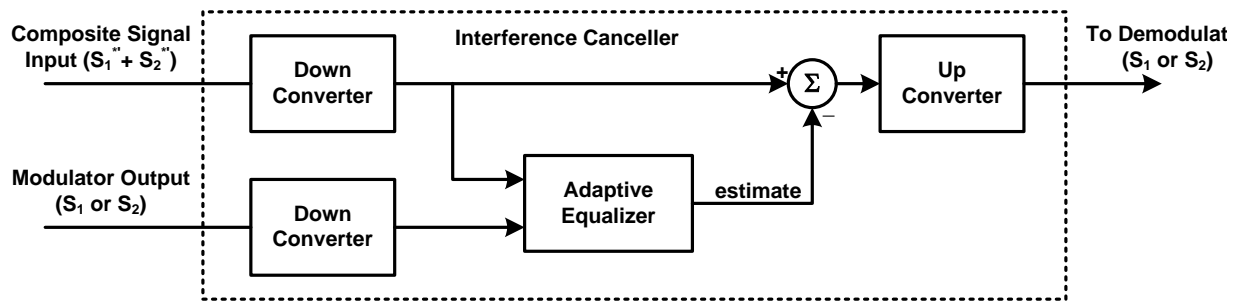


Figure 4: Carrier-in-Carrier Signal Processing Block Diagram

CDM-625 CnC Specifications

Operating Mode	Requires the two carriers in a duplex circuit to share a common frequency
Power Spectral Density Ratio	Ratio of power spectral density, outbound interferer to desired inbound: <u>BPSK, QPSK, 8-PSK/8-QAM</u> -7 dB to +11 dB <u>16-QAM</u> -7 dB to +7 dB
Symbol Rate Ratio	3:1 or less for optimal performance
Inbound/Outbound frequency uncertainty	Within the normal acquisition range of the demod, as follows: <u>Below 64 ksymbols/sec:</u> ± 1 to $\pm (R_s/2)$ kHz, where R_s = symbol rate in ksymbols/sec <u>Between 64 and 389 ksymbols/sec:</u> ± 1 up to a maximum of ± 32 kHz <u>Above 389 ksymbols/sec:</u> ± 1 to $\pm (0.1R_s)$ kHz, up to a maximum of ± 200 kHz
Delay range	0 - 330 ms
Eb/No Degradation	See below
Monitor Functions	Delay, in milliseconds Frequency offset (between outbound interferer and desired inbound): 100 Hz resolution CnC ratio, in dB (ratio of absolute power, outbound interferer to desired inbound)

CnC Carrier Frequency Offset

CnC carriers are normally placed directly on top of each other with the same center frequency for both carriers. For normal CnC operation, the center frequency of the two carriers should be within the acquisition range of the modem for standard carriers.

Margin Requirements

Typical interfering signal cancellation is 28 to 35 dB (depending on the product). The residual interfering signal appears as noise causing a slight degradation of the Eb/No. To compensate for the residual noise, a small amount of additional link margin is required to maintain the desired BER. Margin requirements depend on the product, modulation and power ratios:

For example, the additional margin requirements for the CDM-625 Advanced Satellite Modem are as follows:

Modulation	Nominal Margin*
BPSK	0.3 dB
QPSK/OQPSK	0.3 dB
8-PSK	0.5 dB
8-QAM	0.4 dB
16-QAM	0.6 dB

* Equal power and equal symbol rate for the interfering carrier and the desired carrier, i.e. 0 dB PSD ratio.

Additional margin is required for higher PSD ratio:

- 0.3 dB additional margin at +10 dB PSD ratio

Carrier-in-Carrier Operational Requirements

Carrier-in-Carrier can only be deployed under the following conditions:

- The satellite must be a “Loop-back” satellite (i.e. the transmitting station must be able to receive itself)
- The satellite must be a “Non-processing” satellite (i.e. does not demodulate/ remodulate the signal)

Operational Recommendations

In addition, to minimize “False” Acquisition:

- Use of IESS-315 V.35 Scrambler is highly recommended
- Keep the search delay range as narrow as possible
 - Once the modem has reported the search delay, narrow the search delay range to the nominal reported value +/- 5 ms
 - e.g. if the modem reported delay is 245 ms, narrow the search range to say 240 – 250 ms
- Use external data source (e.g. Firebird) or internal BER tester when testing Carrier-in-Carrier performance
- To prevent self-locking in case the desired carrier is lost, it is recommended that the two carriers have some configuration difference, e.g. use different settings for Spectrum Inversion.

Carrier-in-Carrier Link Design

Carrier-in-Carrier link design involves finding the FEC and modulation combination that provides optimal bandwidth utilization. Just like conventional link design, it is an iterative process that involves trying different FEC and modulation combinations with Carrier-in-Carrier until an optimal combination is found.

For optimal Carrier-in-Carrier performance, it is recommended that the two carriers have similar symbol rate and power. This can be achieved by selecting appropriate MODCODs as shown in following sections.

Symmetric Data Rate Link

Consider the following example:

Satellite & Transponder	Galaxy 18 @ 123° W, 13K/13K
Earth Station 1	Phoenix, AZ 4.6 m
Earth Station 2	Phoenix, AZ 2.4 m
Data Rate	512 kbps / 512 kbps
Availability	≥ 99.97%

The traditional link was based on QPSK TPC 3/4 and required 0.96 MHz of leased BW. The LST¹ summary for the traditional link is as follows:

Link Analysis Description:				
MultiCarrier Txpdr Lease	Link 1	Link 2		
Number of links: <input type="text" value="2"/>				
Modulation	QPSK	QPSK		
Information Rate	512.0	512.0		kbit/s
FEC Code Rate	.7500	.7500		
R-S Code Rate	N/A	N/A		
Clear Sky Eb/No Available	9.3	8.7		dB
Number of Assigned Carriers	1	1		
Transmit ES Code	4_6M	2_4M		
Transmit ES Size	4.6	2.4		m
Receive ES Code	2_4M	4_6M		
Receive ES Size	2.4	4.6		m
Receive ES G/T	24.5	29.0		dB/K

Total Leased Resource Usage:					
LST calculated				Total BW allocated	.9557 MHz
(MultiCarrier Txpdr Lease)				Total BW PEB	.8208 MHz
Total EIRP utilized	20.1	dBW		Total BW utilized	.9557 MHz
Total EIRP available	20.9	dBW		Total BW available	1.0000 MHz
Margin (available-utilized)	.9	dB		Margin (available-utilized)	.0443 MHz

Allocated BW = 0.9557 MHz
PEB = 0.8208 MHz
Leased BW = 0.9557 MHz

Carrier-in-Carrier link design involved trying different Modulation & FEC Code Rates to find the optimal combination:

- 8-QAM, LDPC 2/3 with Carrier-in-Carrier
- QPSK, LDPC 3/4 with Carrier-in-Carrier
- QPSK, LDPC 2/3 with Carrier-in-Carrier
- QPSK, LDPC 1/2 with Carrier-in-Carrier

Link parameters and LST summary for QPSK, LDPC 2/3 with Carrier-in-Carrier is as follows:

¹ LST is Intelsat's Lease Transmission Plan Program.

Includes IF-RF Margin and CnC Margin

Link Analysis Description:			
	Link 1	Link 2	
MultiCarrier Txpr Lease			
Number of links:	2		
Modulation	QPSK	QPSK	
Information Rate	512.0	512.0	kbit/s
FEC Code Rate	.6670	.6670	
R-S Code Rate	N/A	N/A	
Clear Sky Eb/No Available	7.9	7.3	dB
Number of Assigned Carriers	1	1	
Transmit ES Code	4_6M	2_4M	
Transmit ES Size	4.6	2.4	m
Receive ES Code	2_4M	4_6M	
Receive ES Size	2.4	4.6	m
Receive ES G/T	24.5	29.0	dB/K

Total Leased Resource Usage:			
LST calculated		Total BW allocated	1.0747 MHz
(MultiCarrier Txpr Lease)		Total BW PEB	.5777 MHz
Total EIRP utilized	18.6 dBW	Total BW utilized	1.0747 MHz
Total EIRP available	21.4 dBW	Total BW available	1.1000 MHz
Margin (available-utilized)	2.8 dB	Margin (available-utilized)	.0253 MHz

CnC Allocated BW = 1.0747 / 2 = 0.53735 MHz
CnC PEB = 0.5777 MHz
CnC Leased BW = 0.5777 MHz

The link budget summary for the different MODCOD combinations is as follows:

S. No.	Modulation & FEC	Allocated BW (MHz)	PEB (MHz)	Leased BW (MHz)	Savings Compared to Original	PSD Ratio (dB)
1	8-QAM, LDPC 2/3	0.3584	1.1468	1.1468	-20%	2.1
2	QPSK, LDPC 3/4	0.47785	0.6734	0.6734	30%	2.1
3	QPSK, LDPC 2/3	0.53735	0.5777	0.5777	40%	2.1
4	QPSK, LDPC 1/2	0.7168	0.5184	0.7168	25%	2.1

Based on this analysis, QPSK, LDPC 2/3 with Carrier-in-Carrier provides the maximum savings of 40%.

In addition to 40% reduction in Leased Bandwidth, using Carrier-in-Carrier also reduced the required HPA Power by almost 40%:

	Traditional Link (QPSK, TPC 3/4)	CnC Link (QPSK, LDPC 2/3)	HPA Power Reduction
HPA @ 4.6 m	0.7 W	0.5 W	40%
HPA @ 2.4 m	1.5 W	1.1 W	36%

Asymmetric Data Rate Link

As occupied (or allocated bandwidth) of a Carrier-in-Carrier circuit is dictated by the larger of the two carriers, it is strongly recommended that the smaller carrier be spread as much as possible using a lower order modulation and/or FEC, while meeting the PSD ratio spec.

Spreading the smaller carrier using a lower order modulation has multiple benefits:

- Lower order modulation is always more robust
- Lower order modulation uses less transponder power
 - Reduces total transponder
 - Increase available link margin
- Lower order modulation uses less transmit power on the ground
 - This can significantly reduce the BUC/SSPA size by not only reducing the transmit EIRP, but also reducing the BUC/SSPA backoff

Example:

Satellite & Transponder	IS-901 @ 342° W, 22/22 (EH/EH)
Earth Station 1	Africa 4.5 m
Earth Station 2	Africa 3.0 m
Data Rate	3000 kbps / 1000 kbps

The traditional link was based on QPSK, TPC 3/4 and required 3.9 MHz of leased bandwidth. The Carrier-in-Carrier link was based on QPSK, LDPC 3/4 and QPSK, LDPC 1/2 and required 2.8 MHz of leased bandwidth. The savings summary is as follows:

	Original Link			With Carrier-in-Carrier and LDPC			Savings
	Hub to Remote	Remote To Hub	Total	Hub to Remote	Remote to Hub	Total	
Data Rate (kbps)	3000	1000		3000	1000		
Modulation	QPSK	QPSK		QPSK	QPSK		
FEC	TPC 3/4	TPC 3/4		LDPC 3/4	LDPC 1/2		

Occupied BW (MHz)	2.8	0.9	3.7	2.8	1.4	2.8	
Power Eq. BW (MHz)	3.3	0.6	3.9	2.5	0.3	2.8	
Leased BW (MHz)			3.9			2.8	28%

	Original Link	Carrier-in-Carrier and LDPC	Savings
Hub HPA (W)	26.0	20.3	22%
Remote HPA (W)	10.6	6.4	40%

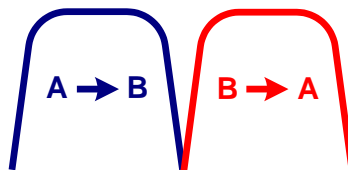
If this link was designed using QPSK, LDPC 3/4 in both directions, it would have required:

Occupied BW	2.8 MHz	
Power Eq. BW	3.0 MHz	7.2% increase in Power Eq. BW
Leased BW	3.0 MHz	7.2% increase in Leased BW
Hub HPA	20.3 W	
Remote HPA	8.3 W	30% increase in Remote power

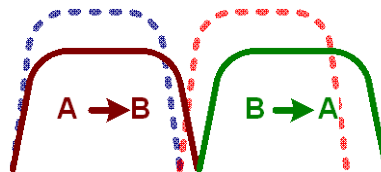
Power Limited Links

Carrier-in-Carrier can provide substantial savings even when the original link is power limited. Spreading the carrier by using a lower modulation and/or FEC along with latest FEC such as VersaFEC can substantially reduce the total power which can then be traded with bandwidth using Carrier-in-Carrier. The concept is illustrated below:

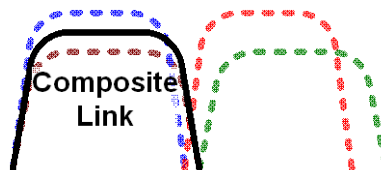
The conventional link is using 8-PSK, TPC 3/4:



Switching to VersaFEC and using a lower order modulation – say QPSK, VersaFEC 0.803 increases the total occupied bandwidth, while reducing the total power equivalent bandwidth:



Now using DoubleTalk Carrier-in-Carrier, the second QPSK, VersaFEC 0.803 carrier can be moved over the first carrier – thereby significantly reducing the total occupied bandwidth and total power equivalent bandwidth when compared to the original side-by-side 8PSK, TPC 3/4 carriers:



Consider the following example:

Satellite & Transponder	IS-901 @ 342° W, 22/22 (EH/EH)
Earth Station 1	Africa 9.2 m
Earth Station 2	Africa 4.5 m
Data Rate	2.048 Mbps / 2.048 Mbps

Original link used 8-PSK TPC 3/4. The Carrier-in-Carrier link used QPSK VersaFEC 0.803. The savings summary is as follows:

	Original Link			With Carrier-in-Carrier and VersaFEC			Savings
	Hub to Remote	Remote To Hub	Total	Hub to Remote	Remote to Hub	Total	
Data Rate (kbps)	2048	2048		2048	2048		
Modulation	8-PSK	8-PSK		QPSK	QPSK		
FEC	TPC 3/4	TPC 3/4		0.803	0.803		
Occupied BW (MHZ)	1.3	1.3	2.6	1.8	1.8	1.8	
Power Eq. BW (MHz)	2.2	1.0	3.2	1.1	0.5	1.6	
Leased BW (MHz)			3.2			1.8	44%

Hub HPA (W)	5.0	2.0	60%
Remote HPA (W)	11.6	4.7	60%

Note: Includes Backoff and 1 dB Feed Loss

Using Carrier-in-Carrier and VersaFEC reduced the leased bandwidth by almost 44% and HPA power by 60%.

Optimization Tradeoffs

With proper selection of Modulation and FEC, Carrier-in-Carrier can be used to achieve multi-dimensional optimization to meet any business requirements:

- Minimize Leased Bandwidth
- Reduce HPA power requirements
- Reduce Antenna size
- Increase availability (margin)
- Or a combination, as needed

The following example illustrates optimization tradeoffs for a cellular backhaul network providing 22 duplex E1s between the hub and 5 remote sites.

Network Topology	Hub Spoke
Hub	7.2 m Antenna
Remotes	5 x 3.8 m Antenna
Total Duplex Links	22 x E1
Transponder	IS-904 @ 60° E, 11/11 (WH/WH)

Legacy Network

The legacy network design was based on TPC 8-PSK 3/4. The bandwidth and power requirements for the legacy network are summarized below:

Modulation & Coding	8-PSK, TPC 3/4
Allocated Bandwidth	56.1 MHz
Power Eq. Bandwidth	58.6 MHz
Total Lease Resource	58.6 MHz
HPA @ Hub	731.8 W
HPA @ Remote1	112.5 W
HPA @ Remote2	136.2 W
HPA @ Remote3	96.1 W
HPA @ Remote4	54.4 W
HPA @ Remote5	55.5 W

Optimization Option A – Optimize Leased Bandwidth and HPA Requirement

Using Carrier-in-Carrier with 8-QAM, LDPC 2/3 provides:

- 43% reduction in Leased BW, and
- 42% reduction in HPA power requirements:

	Legacy Network	With CDM-625	Savings With LDPC & Carrier-in-Carrier
Modulation & Coding	8-PSK, TPC 3/4	8-QAM, LDPC 2/3 with Carrier-in-Carrier	
Allocated Bandwidth	56.1 MHz	31.5 MHz	44%
Power Eq. Bandwidth	58.6 MHz	33.7 MHz	43%
Total Lease Resource	58.6 MHz	33.7 MHz	43%
HPA @ Hub	731.8 W	421.7 W	42%
HPA @ Remote1	112.5 W	65.3 W	42%
HPA @ Remote2	136.2 W	79.0 W	42%
HPA @ Remote3	96.1 W	55.8 W	42%
HPA @ Remote4	54.4 W	31.6 W	42%
HPA @ Remote5	55.5 W	32.2 W	42%

Optimization Option B – Optimize Power and Margin Without Increasing Leased Bandwidth

Using Carrier-in-Carrier with QPSK, LDPC 2/3 provides:

- 68-79% reduction in HPA power requirements, and
- 2.8 dB additional margin for increased availability

while using 19% less leased bandwidth

	Legacy Network	With CDM-625	Savings With LDPC & Carrier-in-Carrier
Modulation & Coding	8-PSK, TPC 3/4	QPSK, LDPC 2/3 with Carrier-in-Carrier	
Allocated Bandwidth	56.1 MHz	47.3 MHz	16%
Power Eq. Bandwidth	58.6 MHz	19.0 MHz	68%
Total Lease Resource	58.6 MHz	47.3 MHz	19%
EIRP Margin	0.0 dB	2.8 dB	2.8 dB Extra Margin
HPA @ Hub	731.8 W	237.3 W	68%
HPA @ Remote1	112.5 W	23.4 W	79%
HPA @ Remote2	136.2 W	28.2 W	79%
HPA @ Remote3	96.1 W	20.0 W	79%
HPA @ Remote4	54.4 W	11.3 W	79%
HPA @ Remote5	55.5 W	11.5 W	79%

Optimization Option C – Reduce Hub Antenna Size, Optimize Power and Margin Without Increasing Leased Bandwidth

Using Carrier-in-Carrier with QPSK, LDPC 2/3 allows for reducing the Hub antenna size to 4.8 m, provides:

- 27-64% reduction in HPA power requirements
- 1.9 dB additional margin for increased availability

while using 19% less leased bandwidth

	Legacy Network	With CDM-625	Savings With LDPC & Carrier-in-Carrier
Antenna @ Hub	7.2 m	4.8 m	
Antenna @ Remotes	3.8 m	3.8 m	
Modulation & Coding	8-PSK, TPC 3/4	QPSK, LDPC 2/3 with Carrier-in-Carrier	
Allocated Bandwidth	56.1 MHz	47.3 MHz	16%
Power Eq. Bandwidth	58.6 MHz	23.3 MHz	60%
Total Lease Resource	58.6 MHz	47.3 MHz	19%
EIRP Margin	0.0 dB	1.9 dB	1.9 dB Extra Margin
HPA @ Hub	731.8 W	533.9 W	27%
HPA @ Remote1	112.5 W	40.4 W	64%
HPA @ Remote2	136.2 W	48.7 W	64%
HPA @ Remote3	96.1 W	34.5 W	64%
HPA @ Remote4	54.4 W	19.5 W	64%
HPA @ Remote5	55.5 W	19.9 W	64%

Carrier-in-Carrier Commissioning and Deployment

Prior to commissioning a Carrier-in-Carrier link, it is critical that the link is fully tested in non Carrier-in-Carrier mode and all system issues including external interference, antenna pointing, cabling, SSPA backoff are resolved. Only after the link is robust, should Carrier-in-Carrier be turned on.

Following procedure is recommended for Carrier-in-Carrier commissioning:

- (1) Turn ON the carrier at Site A. Carrier from Site B is OFF. CnC function is OFF at both sites.
 - Using a spectrum analyzer, measure $(Co+No)/No$ at the input to the modem at Site A.
 - Using a spectrum analyzer, measure $(Co+No)/No$ at the input to the modem at Site B.
 - Measure/record E_b/No at Site B. Make sure there is sufficient margin to account for CnC.
 - Measure/record Receive Signal Level (RSL) at Site B.
- (2) Turn OFF the carrier at Site A. Turn ON the carrier at Site B. CnC function is OFF at both sites.
 - Using a spectrum analyzer, measure $(Co+No)/No$ at the input to the modem at Site A.
 - Using a spectrum analyzer, measure $(Co+No)/No$ at the input to the modem at Site B.
 - Measure/record E_b/No at Site A. Make sure there is sufficient margin to account for CnC.
 - Measure/record RSL at Site A.
- (3) Using $(Co+No)/No$ readings calculate PSD ratio at Site A and Site B. If it is not within specification, make necessary adjustments to bring it within specification and repeat measurements in Step (1) and (2).
 - Also verify that the RSL is within spec.
- (4) Now without changing the transmit power levels, turn ON both the carriers (on the same frequency) and turn CnC ON.
 - Measure/record E_b/No at Site A and B.
 - Measure/record RSL at Site A and B.
 - Now compare the recorder E_b/No (in presence of two overlapping carriers with CnC) with the recorder E_b/No (in presence of a single carrier). E_b/No variation should be within spec for that modulation, FEC and PSD ratio.
- (5) The test can be repeated for different PSD ratio and E_b/No .

Validating Carrier-in-Carrier Performance

Carrier-in-Carrier performance can be easily validated by verifying that E_b/No degradation due to Carrier-in-Carrier is within published specification for the observed Power Spectral Density Ratio. Use the following procedure:

- (1) Setup a conventional side-by-side link of the desired E_b/No
 - a) Carrier-in-Carrier should be OFF
 - b) Record the E_b/No as displayed by the Modems
 - c) Observe the two carriers on a spectrum analyzer and record the PSD ratio

Example Link:

- Full duplex 512 kbps, QPSK, LDPC 2/3 circuit between 4.6 m and 2.4 m antennas

- Recorded $E_b/N_o = 2.6$ dB (at both modems)
- PSD Ratio = 1.2 dB (measured at larger Antenna)

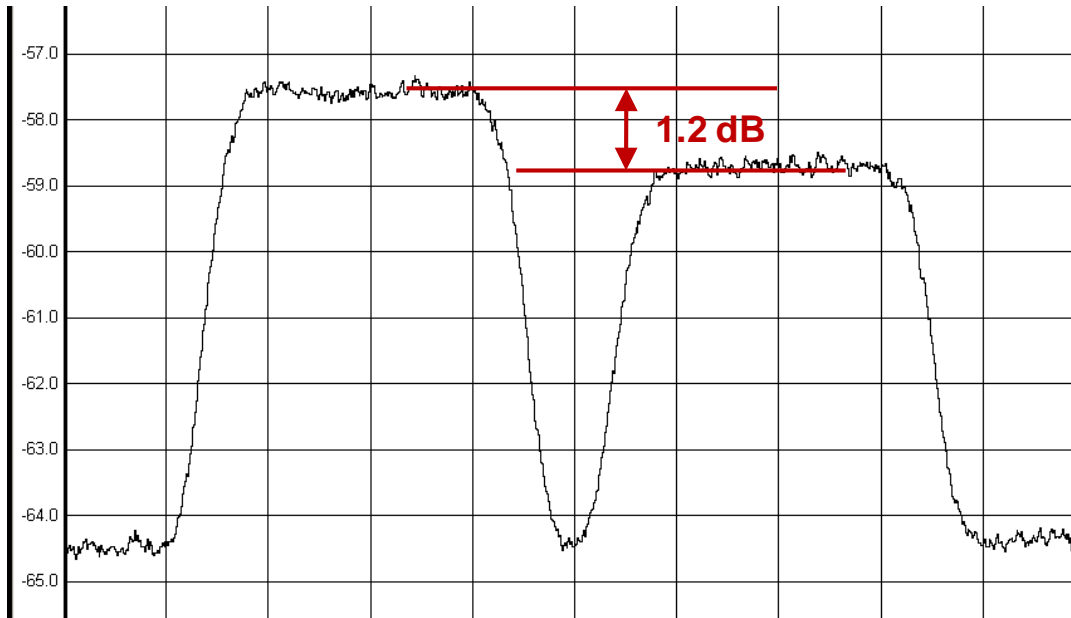


Figure 5: Test Link (Side-by-side) On A Spectrum Analyzer

- (2) Now relocate one of the carriers on top of the other carrier
 - a) Enable Carrier-in-Carrier
 - b) Record the E_b/N_o as displayed by the Modems
- (3) Calculate change in E_b/N_o and verify against specification

Example Link:

- Recorded $E_b/N_o = 2.4$ dB
- Change in $E_b/N_o = 0.2$ dB
- E_b/N_o Degradation (Spec.) at 1.2 dB PSD
= 0.3 dB
- Modem performance is within spec

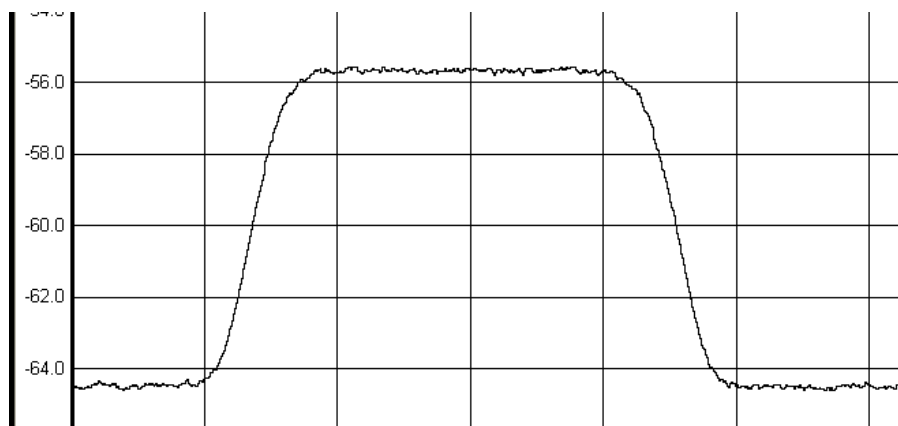


Figure 6: Test Link (With Carrier-in-Carrier) On a Spectrum Analyzer

Carrier-in-Carrier Latency

Carrier-in-Carrier has no measurable impact on circuit latency.

Carrier-in-Carrier and Adaptive Coding and Modulation (ACM)

Carrier-in-Carrier is fully compatible with VersaFEC Adaptive Coding and Modulation (ACM) mode of operation in CDM-625.

Carrier-in-Carrier combined with VersaFEC ACM can provide 100 – 200% increase in average throughput.

Carrier-in-Carrier and Automatic Uplink Power Control (AUPC)

AUPC can be used with Carrier-in-Carrier to compensate for rain fade or other dynamic fade. However, the maximum transmit power level change is limited to 3 dB.

Summary

Comtech EF Data's DoubleTalk Carrier-in-Carrier can provide significant savings in operational expenses.

The following should be considered when evaluating DoubleTalk Carrier-in-Carrier:

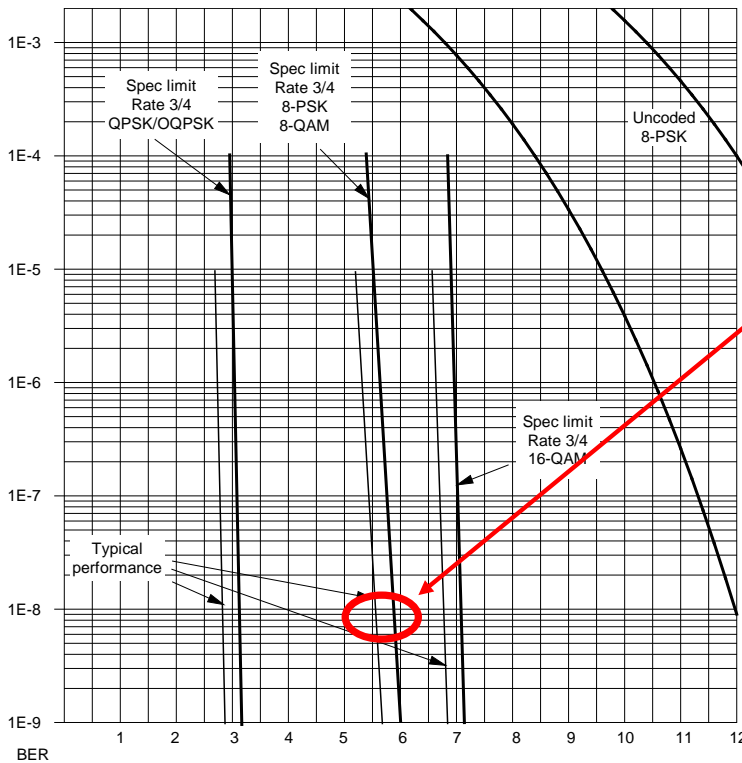
- DoubleTalk Carrier-in-Carrier can only be used for full duplex links where the transmitting earth station is able to receive itself.
- DoubleTalk Carrier-in-Carrier can be used in bandwidth limited, power limited or bandwidth and power limited situations
- The maximum savings is generally achieved when the original link is symmetric in data rate

Appendix

Carrier-in-Carrier Link Budget Calculation

Following steps are involved in calculating the link budget for a Carrier-in-Carrier link:

- (1) Calculate the link budget for each individual carrier in the duplex link, with required CnC margin



Find the Eb/No corresponding to the desired BER

Add CnC Margin

Add any other margin

Use that as Threshold Eb/No for the link budget

- (2) Verify that PSD ratio is within spec (CDM-625)
- (3) Calculate Allocated BW (BW) and Power Equivalent Bandwidth (PEB) for the Duplex link
 - a) $BW_{\text{Duplex Link}} = \text{Greater of } (BW_{\text{Carrier 1}}, BW_{\text{Carrier 2}})$
 - b) $PEB_{\text{Duplex Link}} = PEB_{\text{Carrier 1}} + PEB_{\text{Carrier 2}}$
 - c) $\text{Leased } BW_{\text{Duplex Link}} = \text{Greater of } (BW_{\text{Duplex Link}}, PEB_{\text{Duplex Link}})$
- (4) For an optimal link, the Leased Bandwidth and the Power Equivalent Bandwidth should be equal / nearly equal
- (5) Repeat the link budget process by selecting different Modulation and FEC, until the BW and PEB is nearly balanced

Estimating PSD Ratio

PSD can be estimated from a link budget using Downlink EIRP and Symbol Rate:

$$PSD = \text{Downlink EIRP} - 10 * \text{Log} (\text{Symbol Rate})$$

PSD Ratio Example

Carrier	Downlink EIRP	Symbol Rate	Power Spectral Density
A to B	27 dBW	500 ksps	-29.99 dBW/Hz
B to A	24 dBW	375 ksps	-31.74 dBW/Hz

PSD Ratio (@ A) = - 29.99 - (- 31.74) = 1.75 dB
 PSD Ratio (@ B) = - 31.74 - (- 29.99) = - 1.75 dB

Estimating PSD Ratio from LST

Carrier Information	Link 1	Link 2	
Carrier Type	IPL	IPL	
Performance			BER
Modulation	8-Phase	8-Phase	
Eb/No Threshold	5.6	5.6	dB
C/N Threshold	8.6	8.6	dB
Center Frequency	6014.0	6014.0	MHz
Information Rate (IR)	4096.0	4096.0	kbit/s
Overhead (OH)	.0	.0	kbit/s
Data Rate (IR + OH)	4096.0	4096.0	kbit/s
FEC Code Rate	.6667	.6667	
R-S Code Rate	N/A	N/A	
Transmission Rate	6143.7	6143.7	kbit/s
Bandwidths and Margins			
Filter Roll-off Factor	.40	.40	
Allocated Bandwidth	2.8671	2.8671	MHz
Noise Bandwidth	2.0479	2.0479	MHz
Number of Assigned Carriers Per Link	1	1	

PSD Link 2

$$15.8 - 10 * \text{Log} (2.0479 * 1000000) = -47.3 \text{ dBW/Hz}$$

PSD Ratio

± 1.0 dB

PSD Link 1

$$16.8 - 10 * \text{Log} (2.0479 * 1000000) = -46.3 \text{ dBW/Hz}$$

Per Carrier UL & DL eirp (Clr-Sky)	Link 1	Link 2	
Transmit ES elevation angle	70.4	54.5	deg.
Uplink EIRP per carrier	58.7	57.0	dBW
Pathloss at uplink frequency	199.3	199.5	dB
Gain of 1 m2 antenna	37.1	37.1	dB
Per carrier FD @SC	-103.5	-105.4	dBW/m2
SC pattern advantage @ES	1.8	2.8	dB
Per carrier BE FD arriving @ SC	-101.7	-102.7	dBW/m2
Transponder BE SFD	-79.0	-79.0	dBW/m2
Per carrier input back-off	-22.7	-23.7	dB
Per carrier output back-off	-20.2	-21.2	dB
Transponder BE saturation EIRP	37.0	37.0	dBW
Downlink BE EIRP	16.8	15.8	dBW

Estimating PSD Ratio from Satmaster

Carrier A to B

Space Segment Utilization

	Value	Units
Overall link availability	99.800	%
Information rate (inc overhead)	10.2400	Mbps
Transmit rate	13.6533	Mbps
Symbol rate	3.4133	Mbaud
Occupied bandwidth	4.2667	MHz
Noise bandwidth	66.30	dB.Hz
Minimum allocated bandwidth required	4.2667	MHz
Allocated transponder bandwidth	4.2667	MHz
Percentage transponder bandwidth used	11.85	%
Used transponder power	22.57	dBW
Percentage transponder power used	7.20	%

PSD Carrier A to B

$$= 22.57 - 10 * \text{Log}(3.4133 * 10^6)$$

$$= -42.76 \text{ dBW/Hz}$$

PSD Carrier B to A

$$-40.81 \text{ dBW/Hz}$$

PSD Ratio

± 1.95 dB

Carrier B to A

Space Segment Utilization

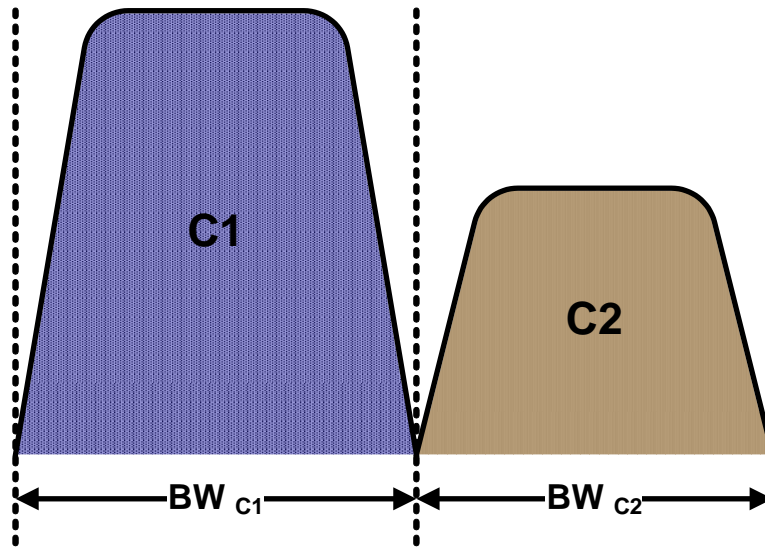
	Value	Units
Overall link availability	99.800	%
Information rate (inc overhead)	10.2400	Mbps
Transmit rate	13.6533	Mbps
Symbol rate	3.4133	Mbaud
Occupied bandwidth	4.2667	MHz
Noise bandwidth	66.30	dB.Hz
Minimum allocated bandwidth required	4.2667	MHz
Allocated transponder bandwidth	4.2667	MHz
Percentage transponder bandwidth used	11.85	%
Used transponder power	24.52	dBW
Percentage transponder power used	8.96	%

CnC Ratio

± 1.95 dB

Estimating PSD Ratio Using Spectrum Analyzer

PSD Ratio or CnC Ratio can also be estimated using a Spectrum Analyzer capable of integrating the signal power in a given bandwidth.



$$\text{CnC Ratio (in dB)} = \text{Power}_{C1} \text{ (in dBm)} - \text{Power}_{C2} \text{ (in dBm)}$$

$$\begin{aligned} \text{PSD Ratio (in dB)} &= (\text{Power}_{C1} - 10 \log \text{BW}_{C1} \text{ (in Hz)}) - (\text{Power}_{C2} - 10 \log \text{BW}_{C2} \text{ (in Hz)}) \\ &= \text{CnC Ratio} - 10 \log (\text{BW}_{C1} / \text{BW}_{C2}) \end{aligned}$$

If the two carriers have same Symbol Rate / Bandwidth, CnC Ratio is same as the PSD Ratio.

Glossary

Allocated Bandwidth

Bandwidth, Allocated Bandwidth or Occupied Bandwidth is the frequency space required by a carrier on a transponder. E.g. a duplex E1 (2.048 Mbps) circuit with 8-PSK modulation, FEC rate 3/4 and 1.4 spacing requires:

- $2.548 \text{ MHz} = 2.048 / (3 * 0.75) * 1.4 * 2$

For a 36 MHz transponder, 2.548 MHz corresponds to 7.078% bandwidth utilization

Power Equivalent Bandwidth

Power Equivalent Bandwidth (PEB) is the transponder power used by a carrier, represented as bandwidth equivalent.

PEB calculation example:

- Transponder EIRP = 37 dBW
- Output Backoff (OBO) = 4 dB
- Available EIRP = $37 - 4 = 33 \text{ dBW} = 10^{3.3} = 1955.26 \text{ Watts}$
- Transponder Bandwidth = 36 MHz
- Power Available / MHz = $1955.26 / 36 = 54.424 \text{ W}$
- If a carrier uses 24 dBW, its PEB = $10^{2.4} / 54.424 = 4.532 \text{ MHz}$

This corresponds to 12.59% of available transponder power.

Leased Bandwidth

Almost all satellite operators charge for the Leased Bandwidth (LBW). Leased Bandwidth or Leased Resource is the greater of the Allocated Bandwidth and Power Equivalent Bandwidth. E.g. if a carrier requires 3 MHz of Allocated BW and 4.5 MHz of PEB, the Leased Bandwidth is 4.5 MHz

Power Spectral Density (PSD)

Power Spectral Density (PSD) is the signal power per unit bandwidth

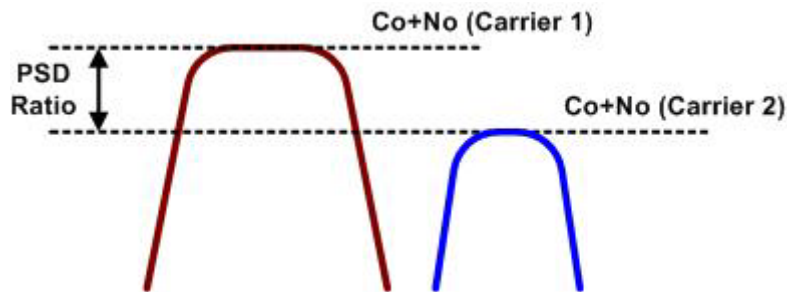
- dBW / Hz or dBm / Hz

Example

- Signal power = 20 dBm
- Signal bandwidth = 500 kHz
- $PSD = 20 - 10 \cdot \log(500 \cdot 1000)$
= -36.99 dBm / Hz

PSD Ratio

PSD ratio is the ratio of power spectral density of the interfering carrier and the desired carrier. If looking at the two carriers side-by-side on a spectrum analyzer:



E_b/N_o

Ratio of Energy per bit (E_b) to Noise density (N_o)

- Unit is dB

C/N

Carrier Power (C) to Noise (N) ratio

- Unit is dB

C/N_o

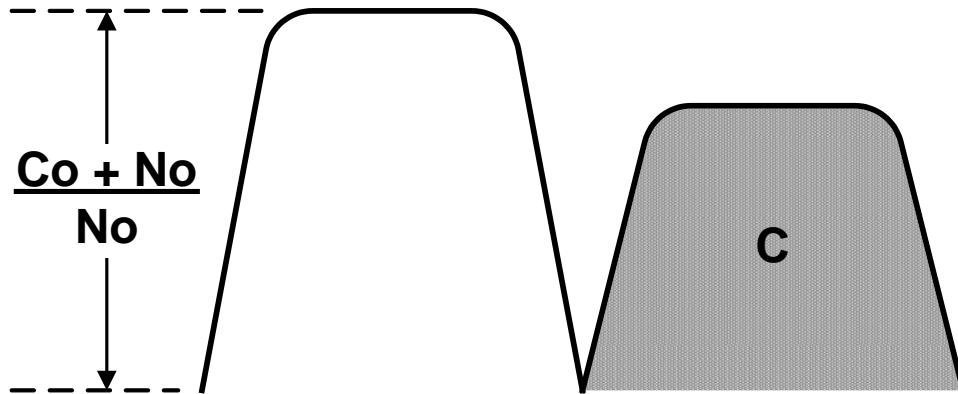
Carrier Power (C) to Noise Density (N_o) ratio

- Unit is dBHz

$(C_o + N_o)/N_o$

(Carrier Density (C_o) + Noise Density (N_o)) to Noise Density (N_o) ratio

- Unit is dB



$$C/N = C/N_o - 10 \log B \text{ [where } B \text{ is bandwidth in Hz]}$$

$$E_b/N_o = C/N_o - 10 \log R \text{ [where } R \text{ is data rate in bits/sec]}$$

$$= C/N + 10 \log B - 10 \log R$$

$$= C/N - 10 \log (\text{Spectral Efficiency})$$

$$E_b/N_o = 10 \log (10^{((C_o+N_o/N_o)/10)} - 1) - 10 \log (\text{Spectral Efficiency})$$

[Spectral Efficiency is in bps / Hz]

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